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An experimental platform for heat pipe solar collector testing

Bin Du [a,b,*], Eric Hu [b], Mohan Kolhe [c]

[a] School of Energy and Environment, Southeast University, Nanjing 210096, China
[b] School of Mechanical Engineering, University of Adelaide, Adelaide, SA 5005, Australia
[c] School of Energy and Resources, University College London (UK), Adelaide, SA 5000, Australia

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ABSTRACT

An experimental platform for testing solar collectors has been designed and built at Southeast University, China. In this article, the structure and the detailed operation of this platform are presented. The performance of an evacuated heat pipe solar collector, in which a heat-pipe is used to transfer the heat from the collector to the water, is investigated experimentally by using the developed platform. The investigation is focused on the instantaneous efficiency and its correlations with the receiver and absorber areas, the effective heat capacity, the incidence angle modifier and the pressure drop. In addition, the theoretical analysis of the solar collector is carried out for these parameters. The thermal behavior and performance of this solar collector is acquired through the experimental results by using this developed platform. This platform is also suitable for experimental investigation of other types of solar collectors.

Contents

1. Introduction

There have been significant scientific and technological developments in the solar collectors. A solar collector is a special kind of heat exchanger that transforms solar radiation energy into heat [1]. Solar thermal utilization for water heating has been developed very rapidly in China [2]. Solar water heating systems have huge demand not only in the Chinese market but also in the international market. There are many solar water heating enterprises in China, which operate under socialized manufacturing structure as it reduces investment risks and also rationalizes resources [2]. At present, solar collectors have been classified as flat plate, glass vacuum tube collector and heat pipe collector. Rojas et al. [3] has tested the thermal performance of the solar flat plate collector according to the ASHRAE 93 and EN 12975-2 standards and compared the different test results under steady

* Corresponding author.
E-mail addresses: bindubill@hotmail.com, zhrybd@hotmail.com (B. Du).

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state and transient conditions. The ASHRAE 93 uses prescribed environmental conditions for a range of collector fluid temperatures for finding the performance of collector under steady state conditions. The EN 12975-2 uses large range of environmental conditions for analyzing the performance of collectors under transient conditions. Villar et al. [4] has presented a transient 3-D mathematical model for flat plate collectors based on mass and energy balances. It can be configured for different configurations of tubes as well as transparent/semi transparent plates. Khoukhi et al. [5] have analyzed the flat plate collector for the effects of convection heat transfer to the thermal loss and performance of the collector considering the absorption-emissivity factor. Budihardjo et al. [6] has developed a mathematical model for the glass vacuum tube collector using water as the heat transfer medium, and included the optics and heat losses property of tubes, and compared the performance of the vacuum tube collector with the flat plate collector. The limitation of this is that it can be used for a low pressure systems and lower circulation rate of the fluid in the vacuum tube collector. Fernandez-Garcia et al. [7] has presented a review of the parabolic-trough solar collectors and their applications to supply the thermal energy upto 400 °C. Mathioulakis et al. [8] has developed a solar collector experimental system comprising of heat pipe and water-storage tank, and analyzed the system performance. The obtained results showed that comparatively high efficiency could be achieved. It can be used for heat-pipe hot water system optimization. Rittidech et al. [9] investigated the plate collector adopting a curved heat pipe and analyzed the influence of solar irradiance and ambient temperature on the collector performance. This analysis incorporates the natural forces of gravity and capillary action. It has additional benefits such as corrosion free operation. Chun et al. [10] have studied the heat pipe solar water heater using different heat transfer medium and analyzed (experimentally) the temperature distribution pattern of the heat pipe under low level solar irradiance. It was focused on finding the most suitable configuration of the system for possible commercialization in Korea. Hussein et al. [11] has investigated transient thermal behavior of heat pipe flat plate collector focusing on the influence of solar irradiance, the material and thickness of heat absorption plate, etc on the thermal performance of the collector. Riffat et al. [12] presented a theoretical model for analyzing heat transfer processes in a thin membrane heat-pipe solar collector, and also the model results were validated through experimental data. Muneer et al. [13] has analyzed the potential of solar thermal energy for Turkish textile industries considering life cycle assessment and relevant economics of solar water heater. Hussein [14] has investigated the effect of wickless heat pipe cross section geometry and its working fluid filling ratio on the performance of flat plate solar collectors experimentally. Different cross section geometries have been included in this study. Hu et al. [15] has investigated the optimal thermal and exergetic performance of solar thermal power system. Yulan et al. [16] analyzed the heat transfer of the compound parabolic concentrator CPC heat pipe vacuum solar collector, and calculated and compared the efficiencies of several collectors. Xue-song et al. [17] has computed the thermal loss coefficient and efficiency of the CPC heat pipe collector. Yunfeng et al. [18] combined a composite parabolic concentrator with a heat pipe plate collector, adopted an iodine-tungsten lamp to simulate the solar irradiance and performed experimental investigation and comparison with the CPC heat pipe plate solar collector and ordinary plate solar collector by focusing on the collector efficiency. Jianhong et al. [19] studied a flat plate solar collector in a solar air conditioning system and their experimental results showed that adding a transparent polycarbonate sheet in the gap between the glazing and the absorber of the collector would reduce the thermal losses and improve the performance of the collector. Jun-feng et al. [20] compared the all-glass vacuum tube solar water heating systems with the heat pipe solar water heating system for instantaneous efficiency under forced circulation conditions and concluded that the heat pipe tube has less heat losses and better performance. The most of the above mentioned researchers mainly focused on flat plat and vacuum tube solar collector.

Investigations aimed at the heat pipe solar collector are comparatively deficient, and mostly concentrated on the CPC heat pipe collector, more specifically on efficiency and thermal losses of the collector. Comprehensive theoretical and experimental researches with more emphasis on the heat pipe solar collector are not reported. In this work, the mathematical model has been presented for doing the performance analysis and also in finding the heat capacity of the heat pipe solar collector has been presented and also the specialized solar collector experimental set-up (test bench/platform) has been developed (Institute of Energy and Environment, Southeast University, Nanjing 210096, China) in China. The main parameters of the heat pipe collector such as temperature, flow rate have been controlled and measured by using two-stage heating through heat exchanger. This developed test bench has been used for performance analysis (through experiments) of the heat pipe solar collector. The effective heat capacity and also the incidence angle modifier of the collector are analyzed for experimental and theoretical results.

2. Experimental system (test bench)

The experimental platform/test bench for the solar collector performance evaluation is illustrated in Fig. 1. It consists of the tilted stand for solar collector, water system, temperature controlling system, flow rate controlling system and related measuring instruments, etc. In this system, the water is used as a heat transfer medium and water supplying circuit consists of the main water tank, pump, pipelines etc, and it is a closed-loop system. The water in the main tank is delivered through the pipeline by using the variable frequency pump, flows through the valve, the filter, the second-stage heater and the flow meter and into the test solar collector. Its temperature increases because of absorption of heat in the collector, and then flows back to the main water tank through the cooling water heat exchanger (as a close-loop system). The pipeline from the main water tank to the solar collector and from the exit of the collector to the temperature measuring point of the working medium is insulated for reducing the thermal losses and also to increase the accuracy of temperature controlling and measurement. There is an endoscope in the pipeline before the inlet of the collector in order to observe whether there are impurities or air bubbles in the working fluid. And there are exhaust valves at the outlet of the collector and in the main water tank so that the hot water can be discharged through the exhaust valves when the measurement procedure is in the high temperature state. In this experimental platform, the water temperature control system comprises the heater in the main water tank, the second-stage heater and the cooling water heat exchanger, and a two-stage heating method are used. The water in the main tank is heated to within the 1% range of the setting inlet temperature of the collector by a power heater at first, and then it is delivered through the pipeline, and is trimmed by the mini-watt second-stage heater, which is thyristor controlled. The second-stage heater has a PID regulation and control function, and it can compare the measured collector inlet temperature of the working fluid with the set temperature and then it sends the error (difference) signal to the control system. If the sampling temperature is lower than the original set temperature, the numerical PID controller switches on the thyristor to heat the working fluid, and if the sampling temperature is the same as the

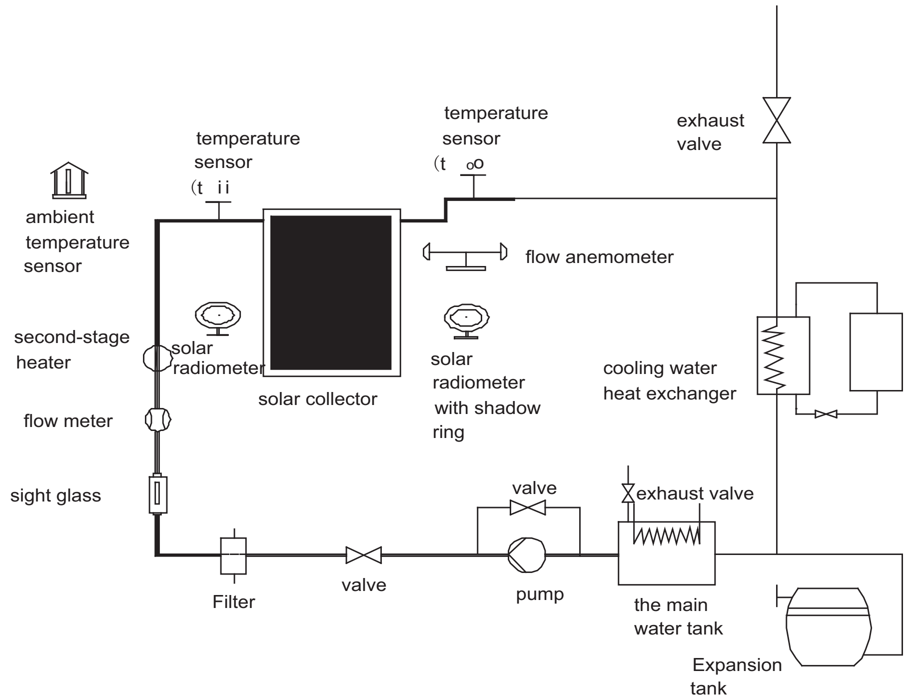

Fig. 1. Experimental system.

set temperature then the control system switches off the thyristor and stops heating, so the working medium can be controlled within the ± 0.1 °C range of the set temperature. The absorbed heat in the collector is transferred to the water (temperature rise), then it flows into the cooling water heat exchanger and is cooled by the cooling water in the heat exchanger and goes back to the main tank. The heat capacity of the main water tank is big enough and the water with fluctuating temperatures from the cooling water heat exchanger is mixed with the water in the main tank so that the water temperature in the tank stabilizes in a short time. There is a mixing pump in the main water tank and it mixes the water thoroughly in order to shorten the time required to reach the heat balance. The flow rate of the working fluid entering the solar collector is measured in real time by using electromagnetic flow meters in the experimental system. The measured sampling data are sent into the control system through the transmitter and the control system carries out the PID calculation and sends a control signal to the frequency converter to regulate the rotating speed of the pump in order to maintain the flow rate within the permitted range of the setting value.

This experimental platform makes use of a collector stand which can be tracked according to the position of the sun. The control system obtains the position variation of the sun through specific calculation, and then sends the position signal of the sun to track control circuit in real time and then it achieves the two-dimensional track through elevating angle and the azimuth of the sun for optimum tracking of the sun. The tracking movement of the solar collector is achieved through the stepper control motor and gear arrangements. In this platform, there is also a manual control apparatus for changing the collector stand tilt angle. The A level PT100 platinum resistors are used to measure the temperature of the working fluid at the inlet and outlet of the test solar collector. The platinum resistor temperature transmitters are connected to the data acquisition system, and the temperature data can be read at every interval of time. During the experiment procedure, the solar radiometer (pyranometer) is placed at the same plane with the collector. And there is also a solar radiometer with a shadow ring (i.e., pyroheliometer) in this experimental system for measuring diffused solar radiation. The velocity of the wind is measured
by the anemometer. During the experiment, the solar collector faces the true South and the tilt angle of the solar collector is 35°.

3. Theoretical analysis

3.1. Instantaneous efficiency

In steady state conditions, the working fluid flowing through the solar collector takes the available energy which is absorbed in the flat plate collector, and the energy losses are due to the heat losses in the system. By using the average temperature (t_m) of the working fluid in the collector, the energy balance of the solar collector is given by:

$$q_u = A_c F_R[G_t(\tau\alpha) - U_L(t_m - t_a)] = mc_f(t_o - t_i) \tag{1}$$

where,

q_u the available output power of the collector (W);
A_c the gross area of solar collector (m^2);
G_t the total solar irradiance intensity (W/m^2);
$\tau\alpha$ the transmittance-absorption product;
U_L solar collector heat transfer loss coefficient (W/(m^2 °C);
t_a ambient temperature (°C);
m the mass flow rate of working fluid (kg/s);
c_f the specific heat capacity of working fluid (J/(kg·°C));
t_i, t_o the inlet and outlet collector temperature of the working fluid (°C);
F_R heat removal factor of the solar collector.

The heat efficiency of the solar collector is the ratio of the available output energy to the solar irradiance received on the collector surface and it is given by:

$$\eta_c = \frac{q_u}{A_c G_t} = F_R\left[\tau\alpha - \frac{U_L(t_m - t_a)}{G_t}\right] \tag{2}$$

Under real conditions, the collector heat transfer loss coefficient is the function of the collector temperature and ambient temperature [1] and it can be expressed using the relation including $(t_m - t_a)$:

$$F_R U_L = c_1 + c_2 (t_m - t_a) \tag{3}$$

Substituting Eq. (3) into Eq. (2):

$$\eta_c = F_R \tau\alpha - c_1 \frac{(t_m - t_a)}{G_t} - c_2 \frac{(t_m - t_a)^2}{G_t} \tag{4}$$

The efficiency curve of the solar collector according to $(t_m - t_a)/G_t$ can be verified through experiments. Accordingly, adopting the receiver area and the absorber area as the benchmark of efficiency calculation, the instantaneous efficiency can be expressed as:

$$\eta_a = \eta_c (A_c / A_a)$$

$$\eta_A = \eta_c (A_c / A_a) \tag{5}$$

where, A_a, A_A are the receiver area and the absorber area of the solar collector (m^2).

3.2. *Effective heat capacity*

The instantaneous energy balance on the solar collector can be expressed as:

$$C \frac{dt_m}{dt} = G_t A_c \eta_c - m c_f \Delta T - A_c U_c (t_m - t_a) \tag{6}$$

where, C effective heat capacity, (J/K);

$$\Delta T = (t_o - t_i), \quad t_m - t_a = (t_i - t_a) + \Delta T/2$$

The effective heat capacity is obtained by integralling the Eq. (6):

$$C = \frac{A_c \eta_c \int_{t_1}^{t_2} G_t dt - m c_f \int_{t_1}^{t_2} \Delta t dt - A_c U_c \left[\int_{t_1}^{t_2} (t_i - t_a) dt + \frac{1}{2} \int_{t_1}^{t_2} \Delta t dt \right]}{t_{m2} - t_{m1}} \tag{7}$$

Under steady state conditions, there is:

$$0 = G A_c \eta_c - m c_f \Delta T - A_c U_c (t_m - t_a) \tag{8}$$

so

$$A_c U_c = \frac{G A_c \eta_c - m c_f \Delta T}{t_m - t_a} \tag{9}$$

through experiments, the effective thermal capacity of the heat pipe solar collector is obtained and i.e., 35,549 J/K.

4. Heat pipe solar collector

A heat pipe solar collector is investigated by using the developed solar collector experimental platform in China. This collector uses the copper- heat pipe and its structure is illustrated in Fig. 2. The external diameter of the evaporator section for this heat pipe is 8 mm, the thickness of pipe wall is 1 mm and the length is 1660 mm. The external diameter of the condensation section for this heat pipe is 14 mm, the thickness of pipe wall is 1 mm and the length is 83 mm. Aluminium fins cover the outside the heat pipe evaporator section; the width of the fin is 62 mm, the length of it is 1670 mm and the thickness is 1 mm. There is an AL/N/AL absorbent coating on the fins, the absorptivity is more than 0.94 and the emissivity is less than 0.10. The heat pipe is inside a vacuum sealed glass tube. The glass tube is made of Borosilicate glass, the external diameter of it is 70 mm, the thickness of tube wall is 2 mm and the length is 1730 mm. The space between the glass tube and the metal pipe remains as a vacuum and the vacuum degree is 5×10^{-2} Pa, as illustrated in Fig. 3.

The solar collector consists of twenty heat collecting tubes and a manifold, as illustrated in Fig. 4. The collector condensation section

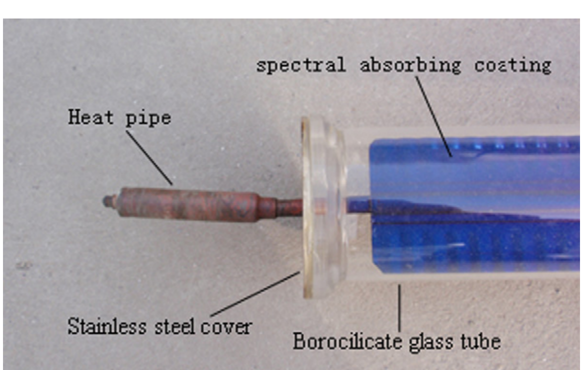

Fig. 2. Heat pipe structure.

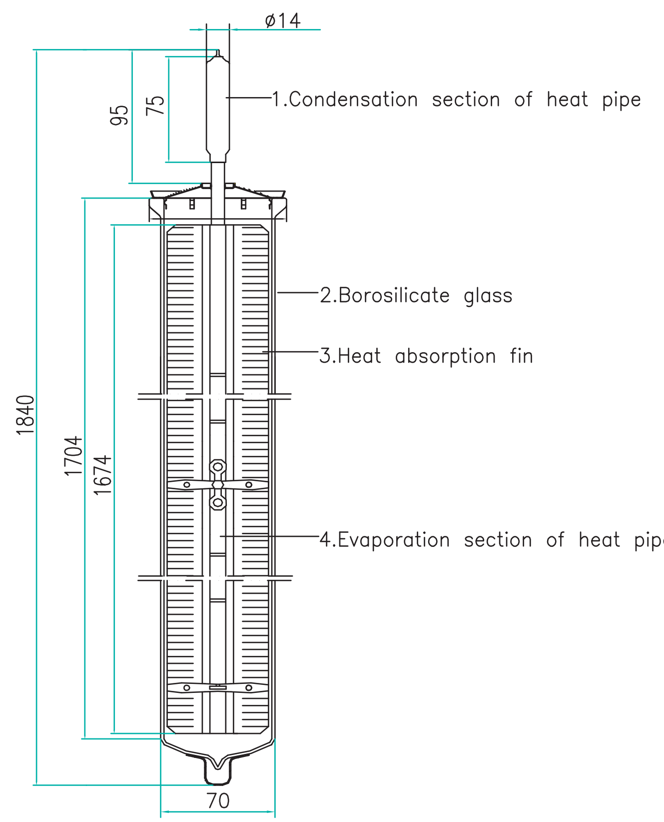

Fig. 3. Heat pipe.

Fig. 4. Heat pipe solar collector.

inserts the main copper tube through the casing and the distance between the casings is 100 mm. There are inlet and outlet water tubes at the two extremities of the main copper tube. The water flows into the main copper tube, absorbs the heat from the heat pipe condensation section, experiences a temperature rise and then flows out. The external diameter of the copper tube is 55 mm and the length is 2140 mm. The main copper tube is wrapped in mineral wool thermal insulation material and encapsulated in the manifold entirely, as shown in Fig. 5. The length of the solar collector is 2.039 m, the width is 1.910 m, the total collector aperture area is 3.89 m^2, the receiver area is 2.253 m^2, the absorber area is 2.07 m^2, its net weight is 74.8 kg and the maximum working pressure is 6 bar.

5. Experimental method and results

5.1. Instantaneous efficiency

During the testing process, if the extent of parameters deviating from the average values is within the range given in Table 1, then it can be regarded as that the collector is in the steady state during this experimental period [21]. The data should be measured when the working fluid is at the different inlet temperatures. The difference between the maximum inlet temperature and the ambient temperature should be more than 40 °C, the time interval between all instantaneous measurements is 3 min, and the experiment period should include at least 12 min preparation period. During the experimental/testing period, the parameters should be collected as follows:

The solar irradiance intensity at the receiver plane of solar collector, G_t(W/m^2);
The diffuse solar irradiance intensity at the receiver plane of solar collector, G_d(W/m^2);
Direct incidence angle, θ, °;
Velocity of ambient wind, u, (m/s);
Ambient temperature, t_a, (°C);
Inlet temperature of working medium, t_i, (°C);
Outlet temperature of working medium, t_o, (°C);
Mass flow rate of working medium, m, (kg/s)

Experimental results are given in Table 2. Based on the theoretical and experimental analysis, the formulas of instantaneous efficiency according to the receiver area and the absorber area are fitted through the following equations.

$$\eta_a = 0.603 - 0.299\frac{(t_m - t_a)}{G_t} - 0.0219\frac{(t_m - t_a)^2}{G_t} \quad (10)$$

$$\eta_A = 0.656 - 0.325\frac{(t_m - t_a)}{G_t} - 0.0238\frac{(t_m - t_a)^2}{G_t} \quad (11)$$

5.2. Effective heat capacity

During the measurement process of effective heat capacity in heat pipe solar collector, the flow rate of the water should be similar to that in experiments of collector efficiency. When the steady state conditions are reached, the following parameters should be measured:

i. the mass flow rate of the working medium;
ii. the inlet, outlet temperature of working medium in collector;
iii. ambient temperature;
iv. solar irradiance intensity;

By using Eq. (9), the average value of A_cU_c in two steady states can be calculated. According to the experimental results, the effective thermal capacity of the heat pipe solar collector is obtained and it is 35,549 J/K.

Table 1
permissible deviation of parameters during experimental period.

Parameters	Permitted deviation range of the average values
Solar irradiance intensity	$\pm$ 50 W/m^2
Ambient temperature	$\pm$ 1 °C
Mass flow rate of the working fluid	$\pm$ 1%
Collector inlet temperature of the working fluid	$\pm$ 0.1 °C

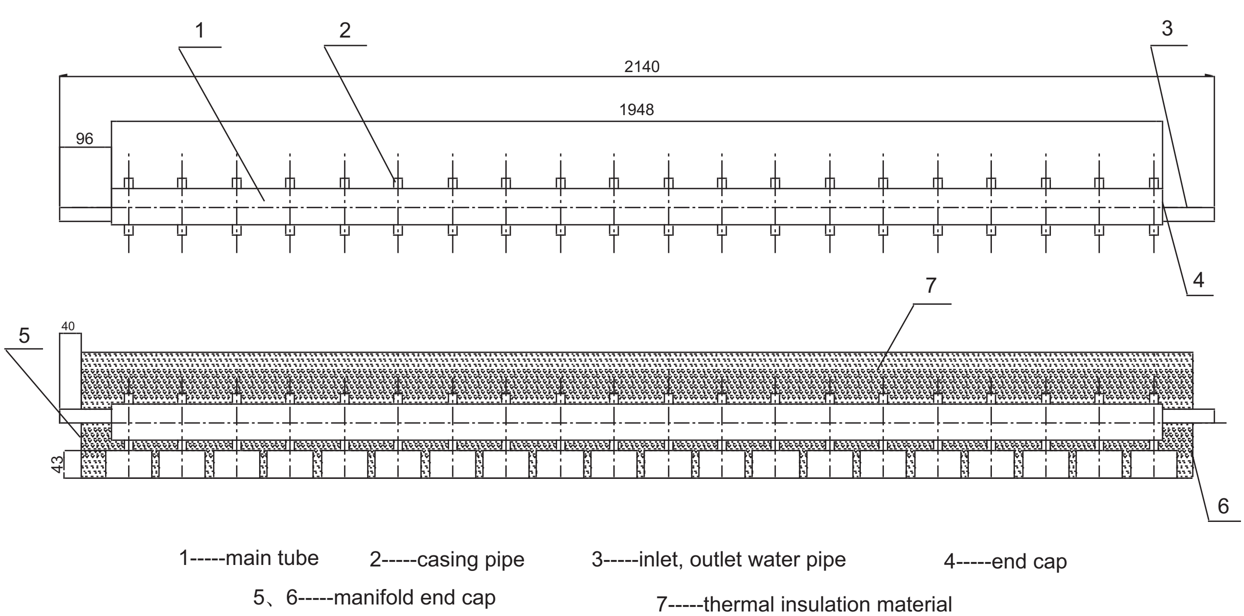

Fig. 5. Manifold.

Table 2
Experimental Data.

Measurement points	G (W/m^2)	G_d/G	(m kg/h)	t_{in} (°C)	t_o (°C)	t_m (°C)	t_a (°C)	$(t_m-t_a)/G(\mathrm{m}^2k/W)$	η
1	859.06	0.19	173.47	25.94	31.78	28.86	28.28	0.000677	0.608
2	878.83	0.18	173.54	25.93	31.88	28.90	28.06	0.000961	0.605
3	888.31	0.19	173.57	25.95	31.92	28.94	27.91	0.001149	0.601
4	999.93	0.11	172.13	39.59	46.18	42.88	23.01	0.019882	0.585
5	956.15	0.24	168.81	44.31	50.72	47.52	28.81	0.019578	0.583
6	933.51	0.19	169.36	44.26	50.54	47.40	27.33	0.021507	0.588
7	1044.58	0.16	169.50	50.27	57.15	53.71	26.39	0.026174	0.575
8	1009.47	0.11	172.58	50.21	56.75	53.48	21.55	0.031630	0.577
9	1020.74	0.11	172.56	50.22	56.83	53.53	21.56	0.031314	0.577
10	889.98	0.16	162.00	84.03	89.37	86.70	28.74	0.065135	0.504
11	923.30	0.17	161.73	84.04	89.53	86.79	28.15	0.063514	0.498
12	895.61	0.17	160.29	88.72	93.95	91.33	27.81	0.070926	0.485
13	906.98	0.16	160.10	88.75	94.03	91.39	27.69	0.070231	0.484
14	906.28	0.17	160.05	88.76	94.07	91.41	27.59	0.070443	0.486
15	901.95	0.16	160.04	88.72	93.96	91.34	27.10	0.071222	0.482
16	905.00	0.16	160.09	88.72	93.91	91.31	26.48	0.071645	0.477
17	885.84	0.16	160.28	88.69	93.72	91.20	25.40	0.074292	0.472
18	861.60	0.17	160.44	88.71	93.58	91.15	25.07	0.076697	0.470

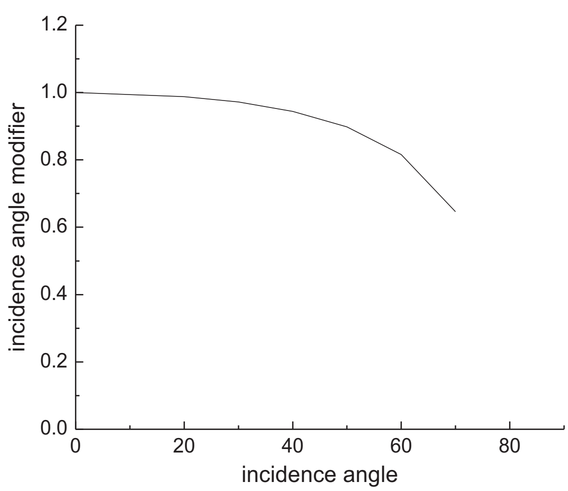

Fig. 6. Collector incident angle modifier.

5.3. The incidence angle modifier

By substituting the incidence angle modifier K_θ into Eq. (2):

$$\eta = F_R(\tau\alpha)_{en}K_\theta - \frac{F_R U_L(t_m - t_a)}{G_t} \tag{12}$$

where,$(\tau\alpha)_{en}$ $(\tau\alpha)$ for normal radiation.

During the experiment, the angle of the solar collector experimental platform should be adjusted. When measuring every data point, to ensure the average temperature of the working medium t_m similar to ambient temperature (± 1 °C), so $(t_m - t_a) \approx 0$. The relation between K_θ and efficiency can be represented as:

$$K_\theta = \frac{\eta_0(\theta)}{\eta_0(0)} = \frac{\eta_0(\theta)}{F_R(\tau\alpha)_{en}} \tag{13}$$

where,

$\eta_0(\theta)$ at $(t_m = t_a)$, the measured instantaneous efficiency at the incidence angleθ;

$\eta_0(0)$ at $(t_m = t_a)$, the measured instantaneous efficiency at normal radiation.

As for the heat pipe solar collector, only the incidence angle modifier in the case of South–North arrangement of the collector should be measured, and it has been illustrated in Fig. 6.

The incidence angle modifier is $K_{50} = 0.898$ when the incidence angle is 50°.

5.4. Pressure drop

The pressure drop is an important parameter for the design of the solar collector. Before measuring the pressure drop, there is a need to ensure that there are no impurities and bubbles in the moving working fluid. Measurements are processed at seven uniform spacing flow rates. The measured parameters are: the temperature of working fluid at the inlet collector t_i, the mass flow rate of working medium m, the pressure difference between the inlet and outlet of collector. During the measurement procedure, the temperature of water remains at 20 ± 2 °C, the flow rate remains within $\pm 1\%$ of the setting flow rate. The experimental data of the heat pipe solar collector is given in Table 3. The calculated data and experimental results are shown in Fig. 7. Based on the measured data, the calculation formula of the collector's pressure drop is obtained and it is:

$$\Delta p = 51838\ \mathrm{m}^2 + 1807\ \mathrm{m} \tag{14}$$

6. Conclusion

An experimental platform/test bench for the testing of solar collector is built at (Institute of Energy and Environment, Southeast University, Nanjing 210096, China) China. Two-stage heating of the working fluid is used and a cooling water heat exchanger is set up in this platform in order to ensure the temperature of the water flowing into the main tank can reach the required range. Simultaneously, the high accuracy electromagnetic flow meter and control instruments are applied in combination with a variable frequency pump to turn the accurate control of the temperature and flow rate during the experiment/testing of the collector. For measuring the incidence angle modifier of the collector, the sun tracing system and transmission device are used in this test bench/platform, so that the angle and posture of the collector can be regulated with a good flexibility. This test bench results show that it guarantees the accuracy of the working fluid temperature and the flow rate of the testing system. The theoretical instantaneous efficiency and effective heat capacity of the heat pipe solar collector is analyzed. The incidence angle modifier and the effective heat capacity of this collector are obtained and analyzed. The equations for instantaneous efficiency and the pressure

Table 3
Pressure drop.

Mass flow rate (kg/s)	0	0.022	0.032	0.047	0.060	0.073	0.087	0.100	0.111	0.121
Pressure drop (Pa)	0	49	127	196	294	392	539	735	833	979

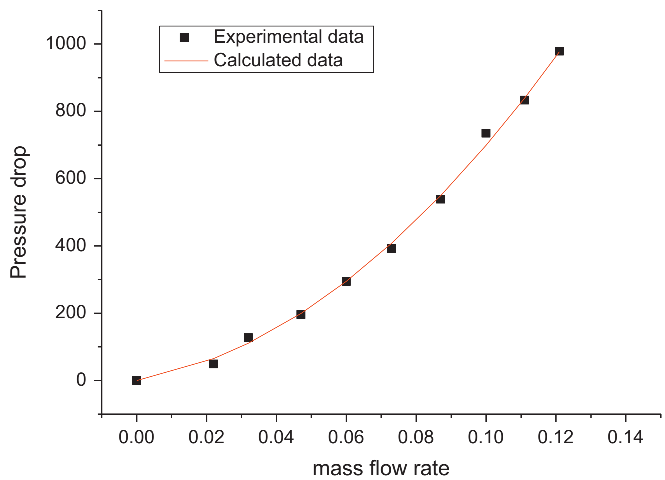

Fig. 7. Pressure drop of collector.

drop have been well fitted by using the experimental data. The experimental results have proved that the developed experimental platform/test bench is stable and reliable, and also it can satisfy the demands of the experimental study (as well as testing) of the heat pipe solar collectors. And this platform is also suitable for experimental investigation/testing of other types of solar collectors such as flat plate solar collector and all-glass solar vacuum tube collector.

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References

[1] Duffie JA, Bekman WA. Solar engineering of thermal processes. John-Wiley & Sons, Inc; 1991.
[2] Han J, Mol APJ, Lu Y. Solar water heaters in China: a new day dawning. Energy Policy 2010;38(1):383–91.
[3] Rojas D, Beermann J, Klein SA. Thermal performance testing of fl -plate collectors. Solar Energy 2008;82(8):746–57.
[4] Molero Villar N, Cejudo Lopez JM, Domınguez Munoz F, Rodriguez Garcia E, Carrillo Andres A. Numerical 3-D heat flux simulations on flat plate solar collectors. Solar Energy 2009;83(7):1086–92.
[5] Khoukhi M, Maruyama S. Theoretical approach of a flat-plate solar collector taking into account the absorption and emission within glass cover layer. Solar Energy 2006;80(7):787–94.
[6] Budihardjo I, Morrison GL. Performance of water-in-glass evacuated tube solar water heaters. Solar Energy 2009;83(1):49–56.
[7] Fernandez-Garcia A, Zarza E, Valenzuela L, Perez M. Parabolic-trough solar collectors and their applications. Renewable and Sustainable Energy Reviews 2010;14(7):1695–721.
[8] Mathioulakis E, Belessiotis V. A new heat-pipe type solar domestic hot water system. Solar Energy 2002;72(1):13–20.
[9] Rittidech S, Wannapakne S. Experimental study of the performance of a solar collector by closed-end oscillating heat pipe (CEOHP). Applied Thermal Engineering 2007;27(11-12):1978–85.
[10] Chun W, Kang YH, Kwak HY, Lee YS. An experimental study of the utilization of heat pipes for solar water heaters. Applied Thermal Engineering 1999;19(8):807–17.
[11] Hussein HMS, Mohamad MA, El-Asfouri AS. Optimization of a wickless heat pipe flat plate solar collector. Energy Conversion and Management 1999;40(18):1949–61.
[12] Riffat SB, Zhao X, Doherty PS. Developing a theoretical model to investigate thermal performance of a thin membrane heat-pipe solar collector. Applied Thermal Engineering 2005;25(5-6):899–915.
[13] Muneer T, Asif M, Cizmecioglu Z, Ozturk HK. Prospects for solar water heating within Turkish textile industry. Renewable and Sustainable Energy Reviews 2008;12(3):807–23.
[14] Hussein HMS, El-Ghetany HH, Nada SA. Performance of wickless heat pipe flat plate solar collectors having different pipes cross sections geometries and filling ratios. Energy Conversion and Management 2006;47(11-12):1539–49.
[15] You Y, Hu EJ. A medium-temperature solar next term thermal power system and its efficiency optimization. Applied Thermal Engineering 2002;22(4):357–64.
[16] Yulan Z, Hong Z, Dongdong Z. Study on thermal efficiency of CPC heat pipe evacuated tubular collectors. Acta Energiae Solaris Sinica 2007;28(9):1022–5.
[17] Xuesong X, Yuezhao Z. Thermal performance of CPC heat pipe heat pipe evacuated tubular collectors. Journal of Nanjing University of Technology 2004;26(6):53–6.
[18] Yunfeng R, Jianlin Y, Hua Z. Experimental research on a compound parabolic concentrator heat pipe type solar collector. Journal of Xian Jiatong University 2007;41(13):291–4.
[19] Jianhong L, Qing J. Experimental research on a high efficient flat plate solar collector. Acta Energiae Solaris Sinica 2001;22(2):131–5.
[20] Jun-feng H, Rui T, Su-ying Y. Comparative analysis of the instantaneous efficiency about two types of solar collector. Energy Engineering 2009(2):25–7.
[21] GB/T 4271-2007: Test methods for the thermal performance of solar collectors.